Towards large-scale calibrations: A statistical analysis on 100 digital 3-axis MEMS accelerometers

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Andrea Prato
INRiM – National Institute of Metrological Research
Division of Applied Metrology and Engineering
Turin, Italy
a.prato@inrim.it

Fabrizio Mazzoleni
INRiM – National Institute of Metrological Research
Division of Applied Metrology and Engineering
Turin, Italy
f.mazzoleni@inrim.it

Francesca R. Pennecchi
INRiM – National Institute of Metrological Research
Division of Applied Metrology and Engineering
Turin, Italy
f.pennecchi@inrim.it

Gianfranco Genta
Department of Management and Production Engineering
Politecnico di Torino
Turin, Italy
gianfranco.genta@polito.it

Maurizio Galetto
Department of Management and Production Engineering
Politecnico di Torino
Turin, Italy
maurizio.galetto@polito.it

Alessandro Schiavi
INRiM – National Institute of Metrological Research
Division of Applied Metrology and Engineering
Turin, Italy
a.schiavi@inrim.it

***Abstract* — Given the growing development and production of low-cost digital MEMS sensors, e.g. accelerometers, gyroscopes, microphones, humidity, pressure and temperature sensors, large-scale measurements are nowadays a possible reality in many different fields, from industry 4.0 to environmental monitoring and smart cities. However, in most of cases, digital MEMS sensors still lack the required metrological traceability needed to provide traceable measurements. As a matter of fact, at present, a preliminary sensitivity value of these sensors is provided by the manufacturers by performing a simple adjustment, without a proper traceable calibration. This is basically due to the impossibility, nowadays, to guarantee large-scale calibration procedures at costs comparable to those of the sensors. For this purpose, it is first of all necessary to know their current technical performances, in terms of sensitivity and associated uncertainties, and then to define possible large-scale calibration methods. In this work, 100 nominally equal 3-axis MEMS digital accelerometers are calibrated with a recently-developed calibration setup at INRiM. Sensitivity values, together with their calibration expanded uncertainties, are compared to statistically analyze their dispersion and distribution within the considered sample. This is the first necessary step towards the development of large-scale calibration methods.**

Keywords—Dynamic calibration, digital MEMS accelerometer, large-scale, sensitivity

I. Introduction

Nowadays, digital MEMS sensors are produced in very huge quantities by manufacturers, in the order of millions per week. Currently, MEMS sensors are mainly (and largely) employed for mobile phone applications, such as accelerometers, gyroscopes, microphones, humidity, pressure and temperature sensors, in which certain levels of precisions are required, but a rigorous metrological traceability is not necessary or even pertinent. However, due to the increasing improvement of inherent technical performance, the reliability and the accuracy of these digital sensors can be considered comparable to the traditional analog measuring instruments, at least within certain boundary conditions or for certain measuring ranges.

Indeed, at present, manufacturers provide a preliminary sensitivity value of digital sensors output data, derived from internal procedures of adjustment and trimming, in terms of scale factors, generally indicated as Least Significant Bit (LSB), according to specific conditions, such as full scale, temperature and other operating conditions, at a given output data rate. However, neither traceable methods are applied nor information about the associated uncertainty is provided. On the other hand, based on suitable metrological calibration procedures, it is possible to highly improve the quality of digital MEMS sensors output data by supplying the sensitivity from traceable methods [1]. To avoid misunderstandings, the meaning of terms used in this paper is that defined in the International Vocabulary of Metrology (VIM) [2].

The "metrological sensitivity", as a result of traceable calibration procedures, is not in conflict with the "adjusted sensitivity" provided by manufacturers, but it represents a further quality parameter of the digital MEMS sensor, allowing to provide the required measurement trustworthiness, with reference to a well-defined traceable physical quantity, relying on the International System of Units (SI) of the Metro Convention. It follows that a digital sensor calibrated against a primary (or secondary) reference standard is reliable to provide accurate and trustworthy data output, within the declared uncertainty, while a digital sensor that is only "adjusted" is not suitable for that purpose.

As it is known, the use of digital sensors (in particular integrated within large or dense sensor networks), is widespread in many advanced engineering applications, including managing of operations and processes, functional monitoring and geo-environmental survey, as well as in many other scientific and technological applications, within the framework of digitalization [3]. As a consequence, the functional performance of these digital sensors, if accurately identified, allows enhancing the trustworthiness, safety, and accuracy of the managed processes, as well as the surveys and the monitoring systems.

However, due to the huge amount of produced MEMS, it is not possible to calibrate every single sensor, as currently done in "traditional" metrology. For this reason, it is necessary to define large-scale calibration methods, schemes or procedures, based on suitable statistical sampling approaches, enabling the MEMS to provide reliable measurement results at a proper confidence level. As stated in the BIPM CCAUV strategy document 2019-2029, «the industry has moved from testing and calibrating every device towards statistical sampling to reduce manufacturing costs while delivering statistically acceptable levels of performance and reliability» [4]. For this purpose, it is first of all fundamental to know the statistical dispersion and the distribution of the sensitivities of these sensors, together with the associated uncertainties, to guarantee their traceability. This work investigates the sensitivity values, in terms of statistical dispersion and distribution, of 100 digital 3-axis MEMS accelerometers, from the same batch, calibrated with a specific system suitable for the simultaneous amplitude calibration of digital 3-axis MEMS accelerometers (in the frequency domain), traceable to the SI, recently developed at INRIM [5].

II. The digital MEMS accelerometers under test

The 100 digital MEMS accelerometers tested in this work are commercial low-power digital 3-axis MEMS accelerometers (STMicroelectronics, model LSM6DSR). These transducers are composed of an acceleration sensing element, a power supply, a charge amplifier, and an analog-to-digital converter. Each digital MEMS accelerometer is connected by a serial cable to a separated IC-board, in which other electronic components are integrated. The external microcontroller (STMicroelectronics, model 32F769IDISCOVERY) acquires the digital samples and provides the required power supply and clock to the MEMS accelerometer. The signal is acquired by means of a Serial Peripheral Interface (SPI), which is a synchronous serial communication interface used for connecting digital devices. The 1-bit signal from the ΣΔ-ADC is then converted through a decimation process and a low pass filter into a standard 16-bit-signed PCM (Pulse Code Modulation) signal [6] with a nominal sampling frequency rate of 1666 Hz. However, sampling frequencies up to -6% of the target, i.e. up to 1560 Hz, can be expected. For this reason, the actual sampling frequency of every MEMS is previously evaluated. The amplitude values range between $-2^{16-1} = -32768\text{Decimal}_{16\text{-bit-signed}}$ (hereinafter abbreviated as $D_{16\text{-bit-signed}}$) and $+(2^{16-1}-1) = +32767\ D_{16\text{-bit-signed}}$, where the digit unit is a signed 16-bit sequence converted into a decimal number. The 100 MEMS accelerometers are shown in Fig. 1.

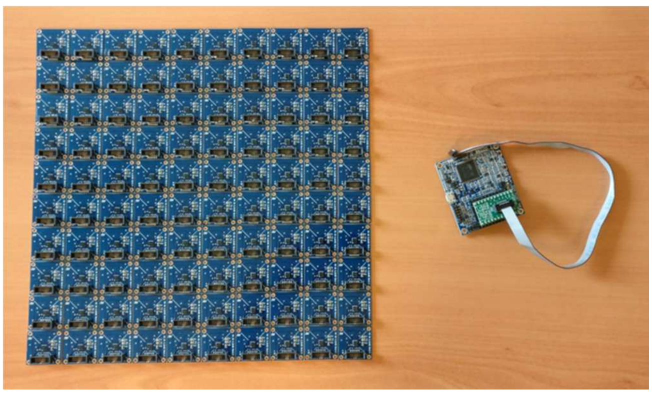

Fig. 1. The 100 digital 3-axis MEMS accelerometers (left) and the external microcontroller (right).

The linear acceleration amplitude sensitivity of a digital MEMS accelerometer, expressed by the manufacturer in terms of mg/LSB, depends on the "full scale" used in the testing condition, and it is conventionally attributed to every sensitive axis of the sensor, for static and dynamic measurements, independently from frequency, without any indication about the associated uncertainty, and is not evaluated through traceable calibration methods. In this work, by using a "full scale" of ±4 g, the declared sensitivity is 0.122 mg/LSB. In decimal units, it corresponds to 0.122 $\text{mg}/D_{16\text{bit-signed}}$, i.e. $1.196\times10^{-3}\ (\text{m/s}^2)/D_{16\text{bit-signed}}$. As commonly used in analog transducers, the sensitivity is expressed as a function of the reference quantity, thus it corresponds to 836 $D_{16\text{bit-signed}}/(\text{m/s}^2)$.

III. Calibration setup and procedure

Calibrations are carried out at 5 Hz, 10 Hz, 20 Hz, 40 Hz, 80 Hz, 160 Hz, 315 Hz, 630 Hz and 1000 Hz, at nearly-constant peak amplitude of 10 m/s^2, by comparison to a reference transducer (in analogy to ISO Standard 16063-21 [7]) with the calibration systems realised at INRiM, consisting of a single-axis vibrating table on which aluminum inclined planes are screwed, as thoroughly described in [5,8]. In Fig. 2, the geometrical principle of the method and the actual inclined plane, on which the digital MEMS accelerometer is fixed at different rotations during calibration on the vibrating table, are shown.

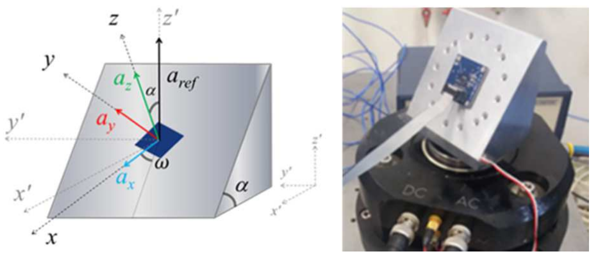

Fig. 2. Inclined plane – 3-D scheme and the calibration set-up: the MEMS is fixed to the inclined plane on the vibrating table.

Measurements are performed in 4 configurations, obtained by fixing the MEMS accelerometer, using an ultra-thin double-sided adhesive tape, to the center of the vibrating table at different angles of tilt and rotation (tilt of 0°and rotation 270°; tilt of 15° and rotation of 90°; tilt of 75° and rotation of 0°; tilt of 75° and rotation of 90°), according to the procedure described in [9].

Systematic effects are caused by spurious components acting on the perpendicular plane with respect to the reference vertical axis *z'*, which are mainly due to the vibrational modes of the inclined aluminum plates and to small horizontal motions of the shaker. Such effects are quantified in terms of amplitude and phase, by means of laser-Doppler velocimetry (Polytec OFV 505), for each inclined plane and for all frequencies, as described in detail in [10,11].

From the 3-axis digital MEMS accelerometer outputs d_i (expressed in $D_{16\text{bit-signed}}$) and the reference accelerations a_i (expressed in m/s^2) along the three axes, both given as 4×3 matrixes (4 configurations and 3 components), the sensitivity matrix $\boldsymbol{S}$ (3×3) can be calculated according to [8]. The main sensitivities S_{ii} and transverse sensitivities S_{ij} are directly obtained from the elements of the sensitivity matrix.

For each MEMS, the 3×3 sensitivity uncertainty matrix ***U*(*S*)** (at a confidence level of 95 %) is obtained from the covariance matrix of the independent variables by applying the law of propagation of uncertainty in its matrix form [12-13]. An extensive description of the uncertainty assessment in matrix form can be found in [5,14]. The independent variables are the reference acceleration generated by the shaker, the tilt angle of the inclined plane, the rotation angle of the MEMS accelerometer on the plane, and the systematic spurious components, in terms of amplitude and phase difference along the three axes, previously described. Standard uncertainty associated to the reference acceleration, measured by a single axis reference transducer (PCB model 080A199/482A23), along the z'-axis of the reference system, derives from the Calibration and Measurement Capabilities (CMC) declared by INRiM [15], which is around 0.8% in terms of relative expanded uncertainty from 5 Hz to 1 kHz. Inclined planes were manufactured with numerical control machines (tolerance of ± 0.1°), therefore a type B uncertainty contribution with a half-width of 0.1° is associated to the tilt angle. Since the rotation of the MEMS is manually performed, by means of a centring mask with a tolerance of ± 0.1°, a type B uncertainty contribution with a half-width of 1° is cautiously associated to the rotation angle. Amplitudes and phase differences of the systematic spurious components were evaluated from five repeated measurements; hence a type A uncertainty contribution (standard deviation) is associated to these terms. According to previous works [5,14], the overall expanded uncertainties of the main sensitivities, in a single calibration, ranged, on average, from 0.5 % to 4 %.

IV. CALIBRATION RESULTS

Experimental results of the 100 MEMS accelerometers from 5 Hz to 1000 Hz, in terms of main sensitivities values along *x*-, *y*- and *z*-axis, expressed in $D_{16\text{-bit-signed}}/(m/s^2)$, and the associated relative expanded uncertainties (at a confidence level of 95 %), are summarized in Figs. 3, 4 and 5 and in Figs. 6, 7 and 8, respectively, as box plots. Sensitivities along *x*- and *y*-axis range between 615 $D_{16\text{-bit-signed}}/(m/s^2)$ and 1025 $D_{16\text{-bit-signed}}/(m/s^2)$, with relative expanded uncertainties around 1.2 % at 5 Hz, and around 0.4 % from 10 Hz to 1 kHz, whereas *z*-axis sensitivities are between 251 $D_{16\text{-bit-signed}}/(m/s^2)$ and 896 $D_{16\text{-bit-signed}}/(m/s^2)$, with relative expanded uncertainties around 0.9 % at 5 Hz and 0.9 % from 10 Hz to 1 kHz. Higher uncertainties at 5 Hz are due to the vibration generation system (shaker), which is less stable at such low frequency and at a peak amplitude of 10 m/s^2. It is worth noting that the nominal value declared by the manufacturer is 836 $D_{16\text{-bit-signed}}/(m/s^2)$ without any indication of uncertainty. Transverse sensitivities are, on average, around 2 % of the main sensitivities, with increasing values at increasing frequencies from around 0.2 % up to around 10 %. This is due to the fact that at higher frequencies the variability of the main sensitivities terms is quite large along *z*-axis with respect to the other two axes, therefore transverse terms increase to compensate for such behavior.

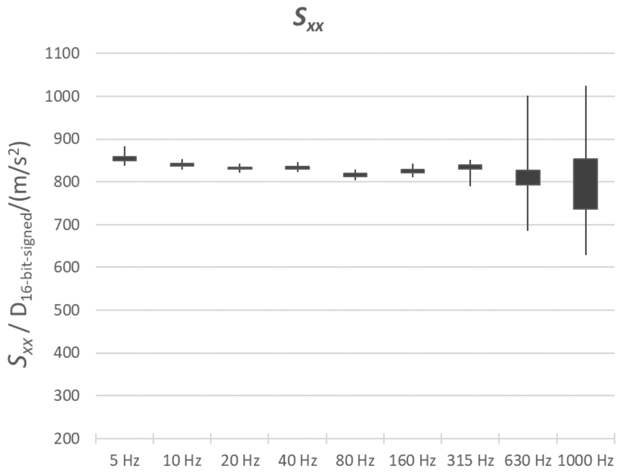

Fig. 3. Sensitivities along *x*-axis of the 100 MEMS as function of frequency.

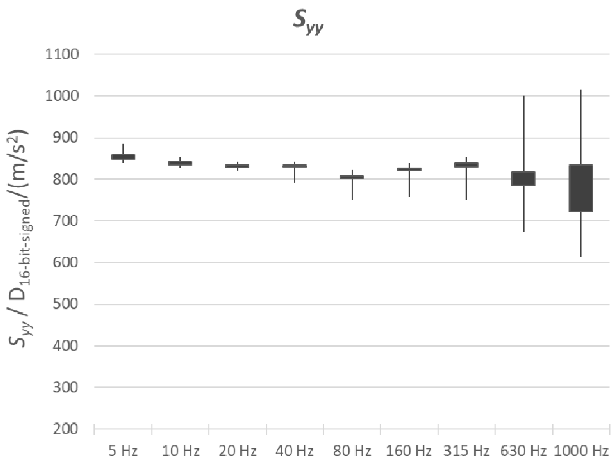

Fig. 4. Sensitivities along *y*-axis of the 100 MEMS as function of frequency.

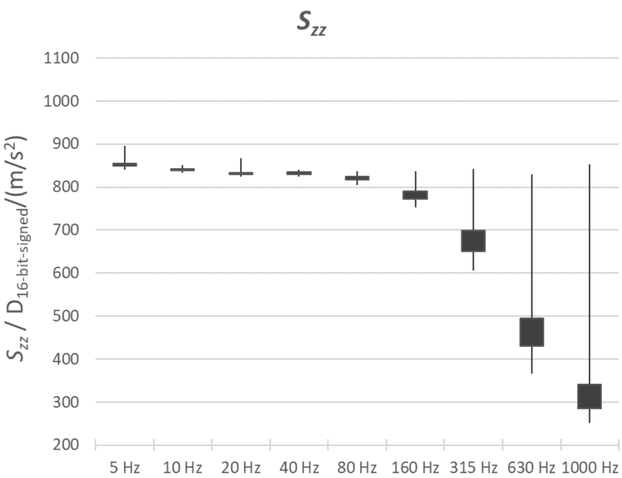

Fig. 5. Sensitivities along *z*-axis of the 100 MEMS as function of frequency.

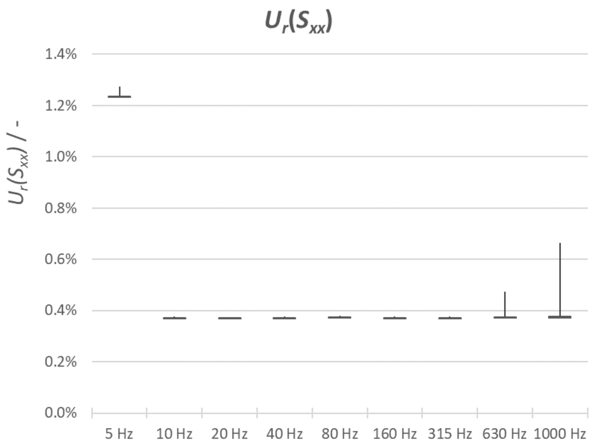

Fig. 6. Relative expanded uncertainties of the 100 MEMS *x*-axis sensitivities as function of frequency.

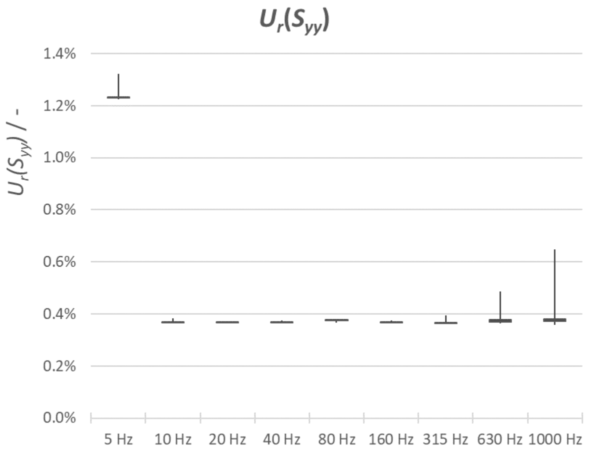

Fig. 7. Relative expanded uncertainties of the 100 MEMS *y*-axis sensitivities as function of frequency.

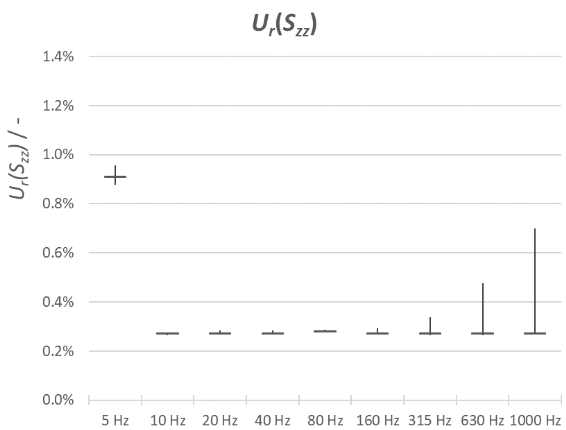

Fig. 8. Relative expanded uncertainties of the 100 MEMS *z*-axis sensitivities as function of frequency.

The distribution of the experimental data for each frequency and each vibrating axis is significantly non-normal as shown by the chi-squared test applied to the 100 MEMS sensitivity data ($p < 0.05$). As an example, the experimental distribution of *x*-, *y*- and *z*-axis sensitivity values at 5 Hz and 1000 Hz are depicted in Figs. 9, 10, 11, 12, 13 and 14. In general, the obtained distributions are non-normal, since they are clearly skewed (non-symmetric). The shape of the distributions varies both with the frequency and with the vibration axis, since some are skewed to the left, while others to the right. Therefore, no relationship with these two parameters seems to occur.

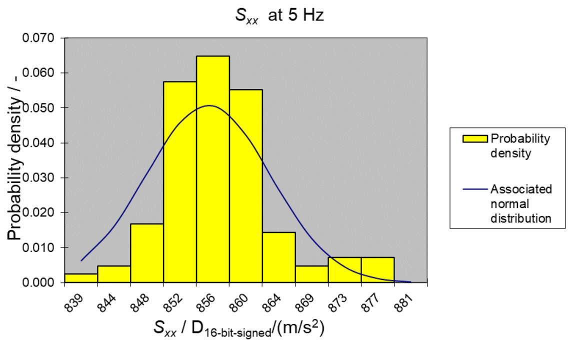

Fig. 9. Distribution of the 100 MEMS *x*-axis sensitivities at 5 Hz.

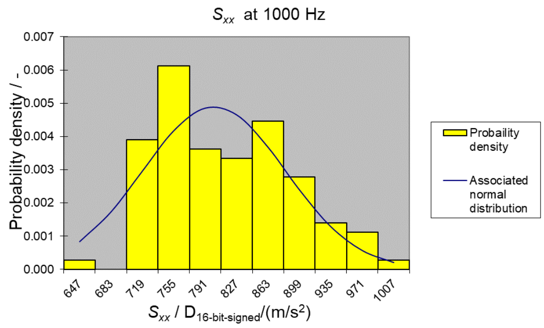

Fig. 10. Distribution of the 100 MEMS *x*-axis sensitivities at 1000 Hz.

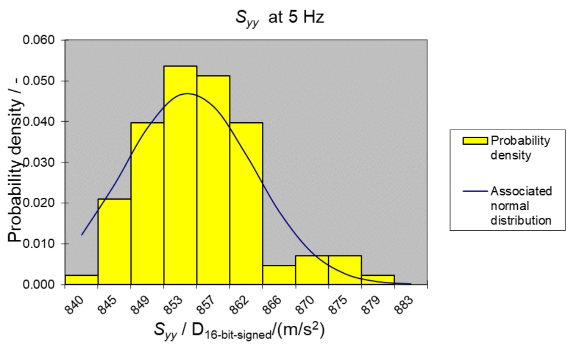

Fig. 11. Distribution of the 100 MEMS *y*-axis sensitivities at 5 Hz.

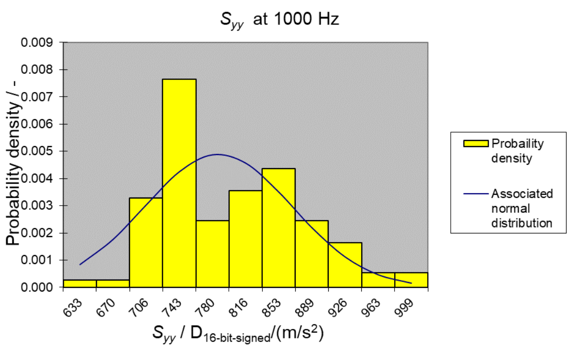

Fig. 12. Distribution of the 100 MEMS *y*-axis sensitivities at 1000 Hz.

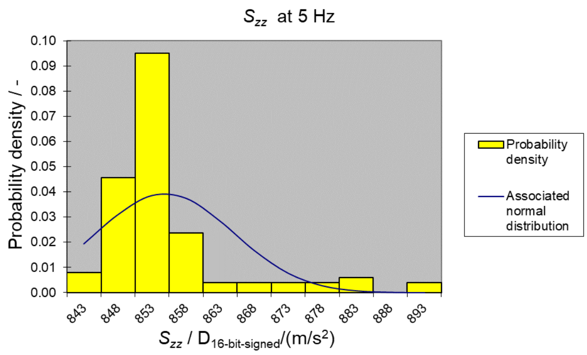

Fig. 13. Distribution of the 100 MEMS *z*-axis sensitivities at 5 Hz.

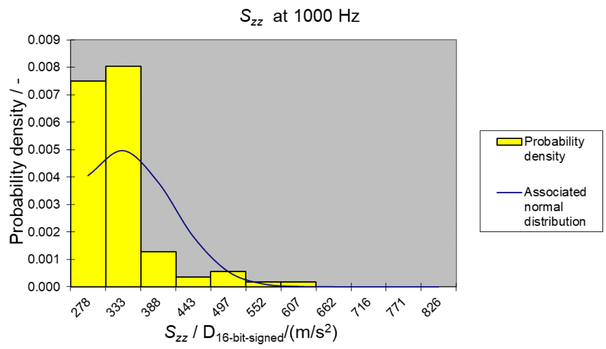

Fig. 14. Distribution of the 100 MEMS *z*-axis sensitivities at 1000 Hz.

V. Discussion

Variability of sensitivity values along *x*- and *y*-axes is rather small at most of the considered frequency values, though showing an increasing dispersion at higher frequencies. The sensitivity mean values are almost constant. Along *z*-axis, instead, sensitivities decrease with frequency, with an even larger dispersion at high frequencies. Furthermore, some *z*-axis sensitivity values are much higher than the others, mainly at high frequencies, as shown in Fig. 5, hence they might be considered as outliers, based on the statistical analysis. Uncertainties related to *x*- and *y*-axis are larger than those related to the *z*-axis due to the contribution of the rotation angle, which is irrelevant for the vertical axis. Higher uncertainties at 5 Hz are due to the vibration generation system (shaker), which is less stable at such low frequency and at a peak amplitude of 10 m/s^2. Besides, sensitivity values are slightly lower than the nominal value declared by the manufacturer, i.e., 836 $D_{16\text{-bit-signed}}/(m/s^2)$.

The distribution of the sensitivity terms along the three axes is highly skewed (non-normal) in the considered frequency range 5–1000 Hz. This means that the manufacturing processes of these MEMS accelerometers, in particular the sensing elements, and the adjustment of their sensitivities are affected by systematic effects. Such results will be important to develop suitable statistical methods aimed at performing large-scale calibrations.

VI. Conclusions

This work aims to assess the statistical dispersion and distribution of the sensitivities of 100 nominally identical digital 3-axis MEMS accelerometers, along *x*-, *y*- and *z*-axis, calibrated with a specific system, suitable for the simultaneous amplitude calibration of 3-axis accelerometers (in the frequency domain), traceable to the SI and recently developed at INRIM.

In general terms, sensitivity mean values of the 100 MEMS along *x*- and *y*-axes are almost constant in the considered frequency range, while decrease with frequency along *z*-axis. In all cases, higher dispersion at increasing frequencies is found. Relative expanded uncertainties variability is small with frequency, with values around 0.4 % along *x*- and *y*-axis, and 0.3 % along *z*-axis from 10 Hz to 1 kHz. At 5 Hz, larger uncertainties are found to the vibration generation system which is less stable at that specific frequency. Furthermore, it is found that the distribution of the 100 experimental MEMS sensitivities for each frequency and axis is significantly non-normal, therefore such behavior will have to be taken into account in the future when evaluating suitable statistical large-scale calibration methods.

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